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CALIPSO-inferred aerosol direct radiative effects: bias estimates using ground-based Raman lidars

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Aerosol direct radiative effect (DRE)

- The change in radiative flux caused by the presence of aerosols (both natural and anthropogenic)
  - How aerosol affects the Earth's radiation balance in the present climate
  - Estimation of aerosol radiative forcing (i.e. anthropogenic aerosols)

  (Bellouin et al. Nature 2005, Kaufman GRL 2005, Su et al. JGR 2013)

Satellite estimates of aerosol DRE

- Many estimates of the shortwave (SW) aerosol DRE have been made using passive remote sensors (Yu et al. ACP 2006 and references therein)
  - Longwave aerosol DRE is usually much smaller
  - Mostly MODIS-based

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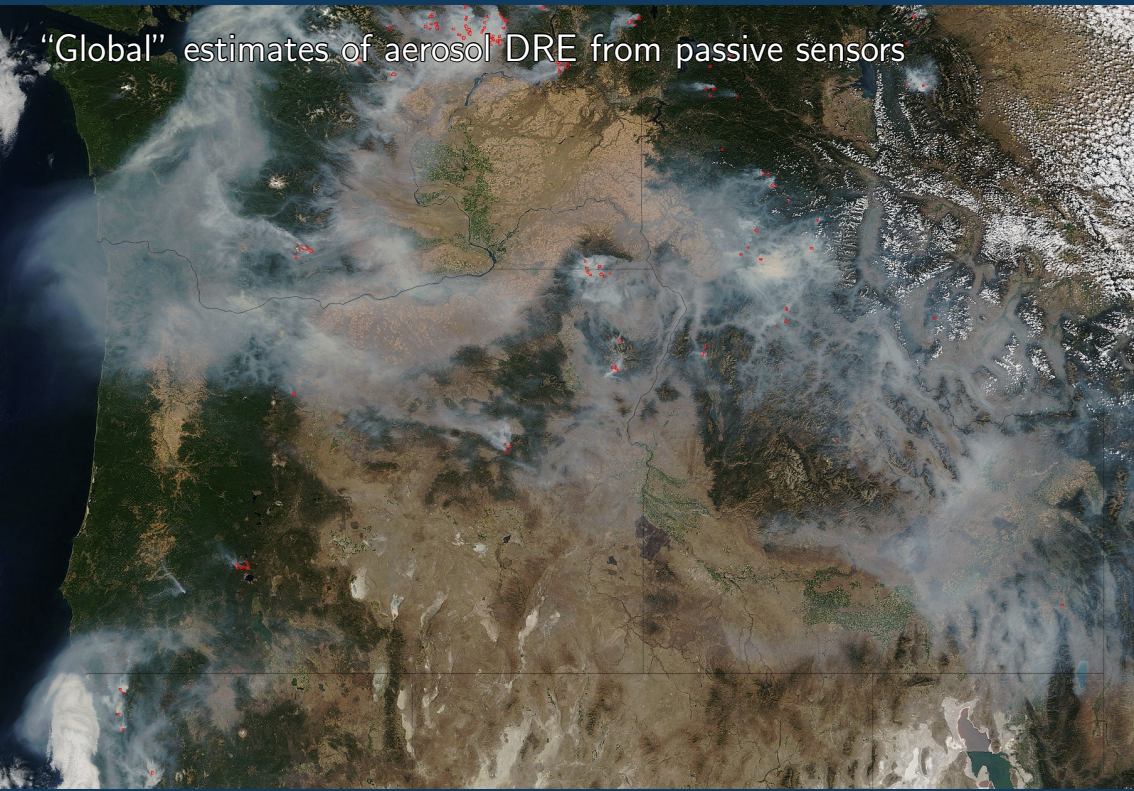
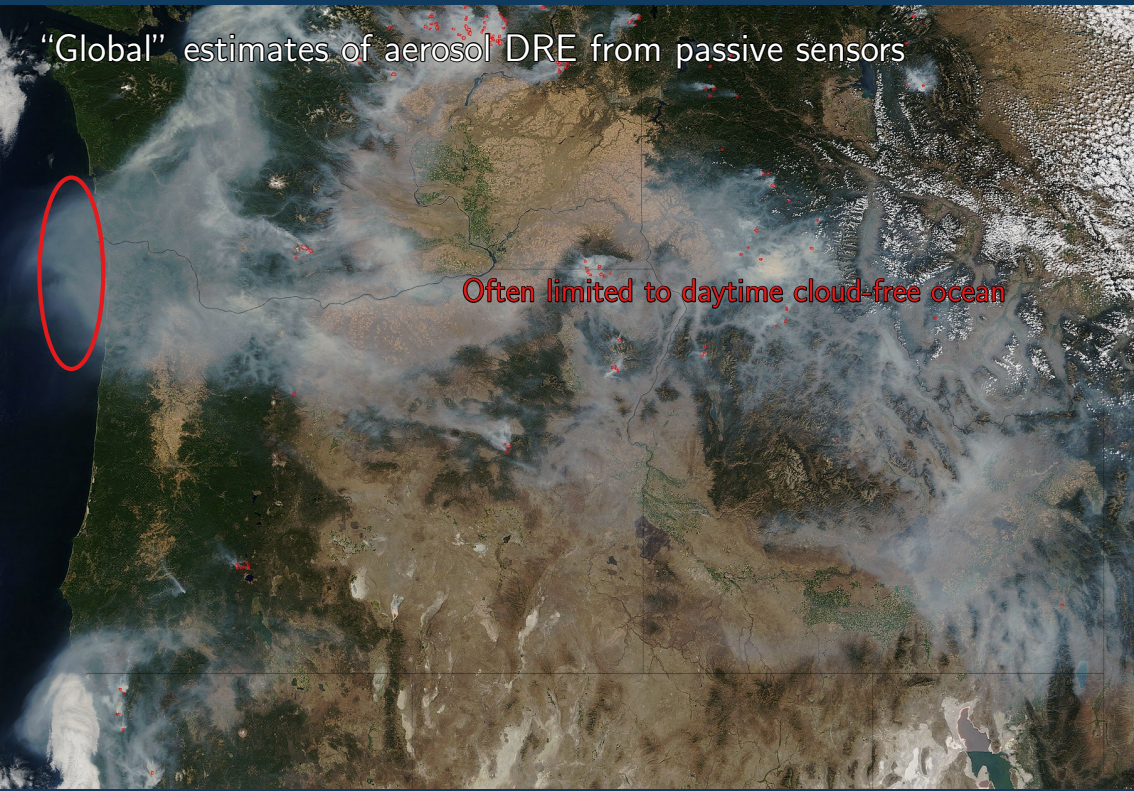
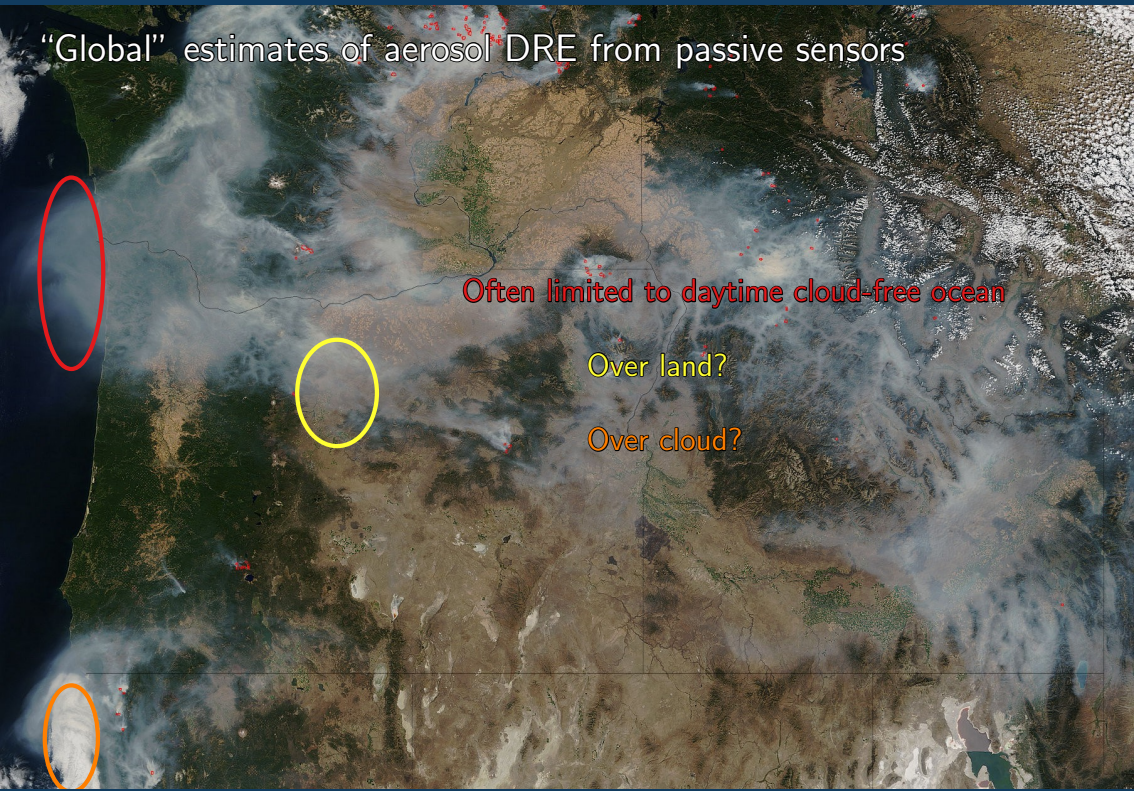
- The global-mean SW aerosol DRE at the TOA is about $-5.0\ Wm^{-2}$
  - The presence of aerosols increases the amount of reflected SW by 5.0 Wm^{-2}


"Global" estimates of aerosol DRE from passive sensors


"Global" estimates of aerosol DRE from passive sensors
Often limited to daytime cloud-free ocean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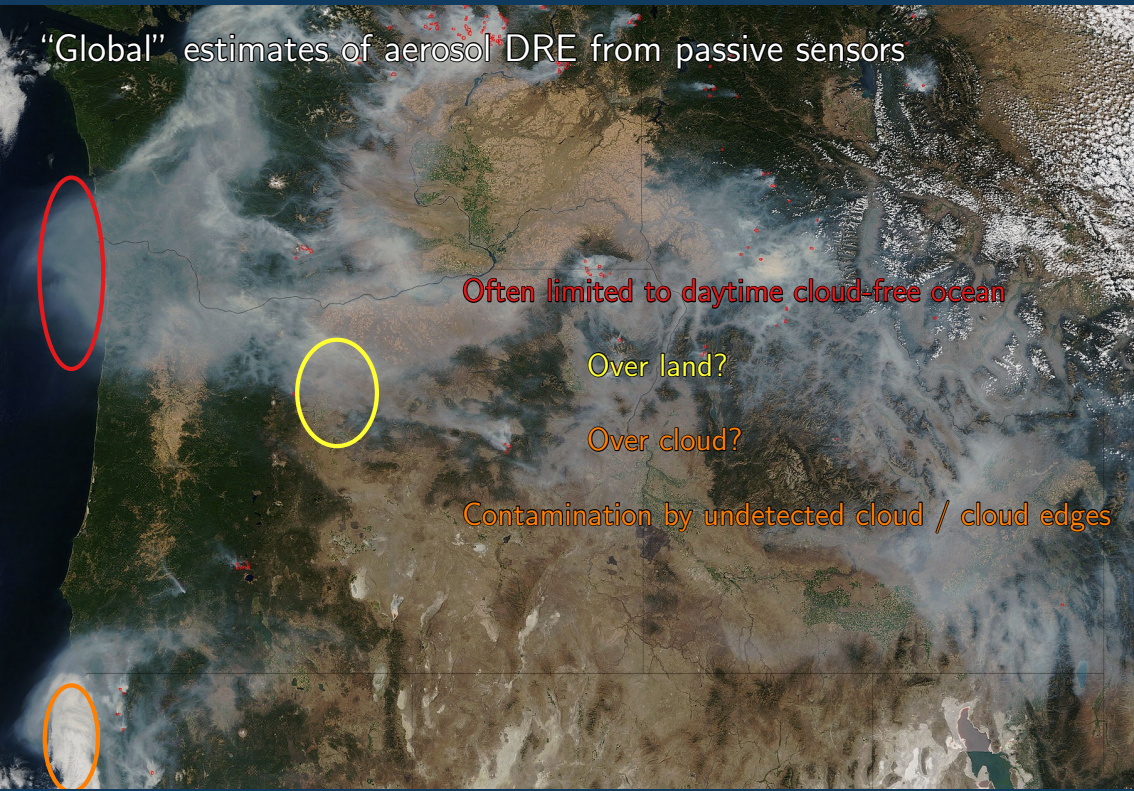
Over land?
Over cloud?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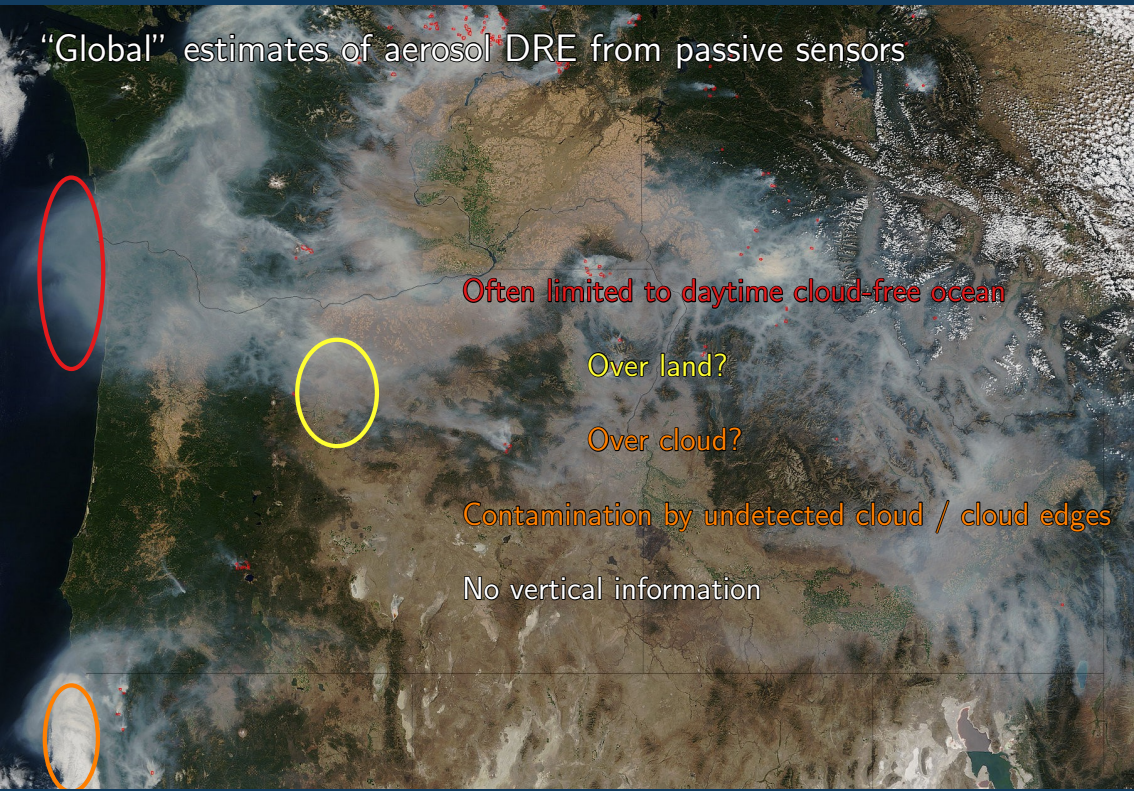
Contamination by undetected cloud / cloud edges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No vertical information

CALIPSO

- Vertically-resolved aerosol properties over all surface types during both day and night
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- Recent studies have made new estimates of the global-mean aerosol DRE using CALIPSO:

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Passive sensor-based	$-5.0\ Wm^{-2}$	N/A
(Yu et al. *ACP* 2006)		
CALIPSO-based	$-3.21\ Wm^{-2}$	$-0.61\ Wm^{-2}$
(Oikawa et al. *JGR* 2013)		
CALIPSO-based	$-2.6\ Wm^{-2}$	$-1.9\ Wm^{-2}$
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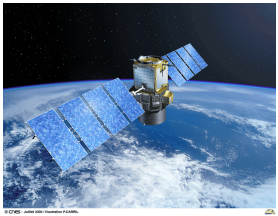
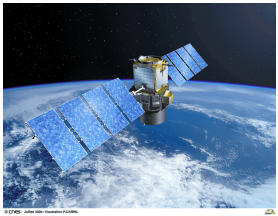
Why are CALIPSO-based estimates significantly smaller in magnitude than the passive sensor-based ones?

CALIPSO



ARM Raman lidars (RL)

CALIPSO



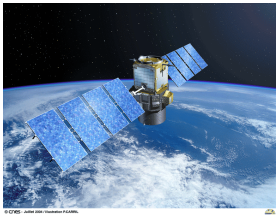
❶ Radiative flux → aerosol extinction → assumed lidar ratio (ratio of extinction-to-backscatter)

ARM Raman lidars (RL)

❶ Direct extinction measurements

(no critical assumptions)

CALIPSO



1. Radiative flux → aerosol extinction → assumed lidar ratio (ratio of extinction-to-backscatter)
2. Is all radiatively-significant aerosol detected? (Kacenelenbogen et al. 2014, Rogers et al. 2014, Thorsen et al. 2015)

ARM Raman lidars (RL)

1. Direct extinction measurements (no critical assumptions)
2. Strong signals from aerosols (it's closer)

Methodology

- Collocate ($\pm$200 km, $\pm$2 hr) CALIPSO aerosol products (VFM, ALay) and ARM RL-FEX product over a 5 year period at SGP, 4 year period at TWP
- Calculate aerosol DRE using the NASA Langley Fu-Liou radiative transfer model:

$$DRE(TOA) = [F^{\downarrow}(TOA) - F^{\uparrow}(TOA)]_{\text{aerosol}} - [F^{\downarrow}(TOA) - F^{\uparrow}(TOA)]_{\text{no aerosol}}$$

$$DRE(SFC) = [F^{\downarrow}(SFC) - F^{\uparrow}(SFC)]_{\text{aerosol}} - [F^{\downarrow}(SFC) - F^{\uparrow}(SFC)]_{\text{no aerosol}}$$

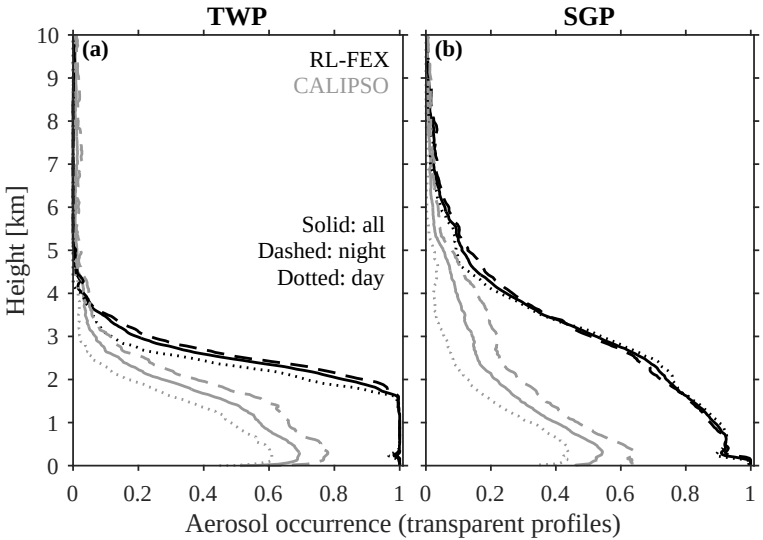
- *Modify RL retrievals to mimic CALIPSO to test the effect of
  ❶ lidar ratio assumptions and
  ❷ detection sensitivity

*Avoiding using the CALIPSO data directly because of wavelength difference between the lidars

❶ About +10% bias in the aerosol DRE due to the lidar ratio

Detection sensitivity

Detection sensitivity



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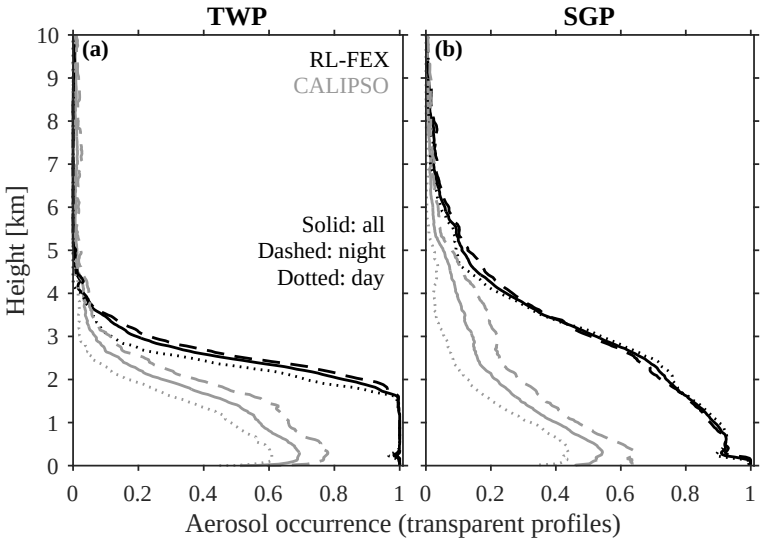

Is this undetected aerosol radiatively-significant?

Effect of detection sensitivity

- Method to force RL aerosol occurrence profile to match CALIPSO's by removing aerosol in each collocated overpass.

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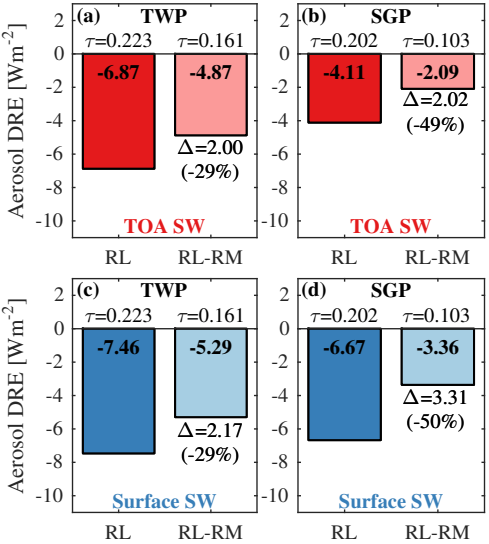

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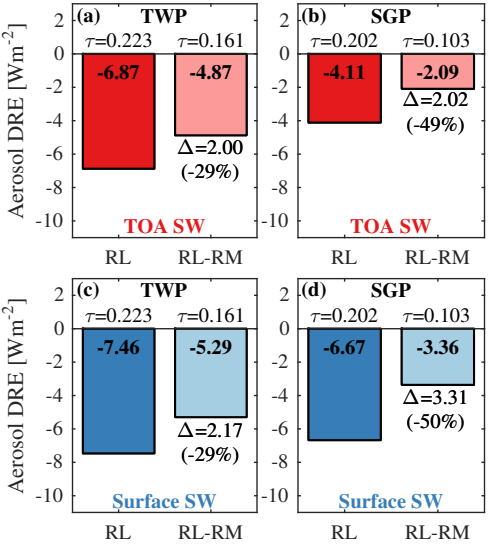

CALIPSO's lack of sensitivity causes a significant reduction of 30–50% in the magnitude of the aerosol DRE

Global implications

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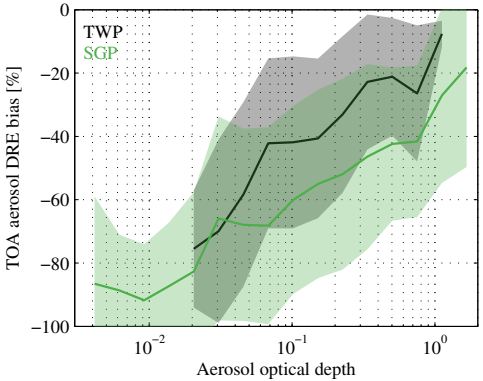


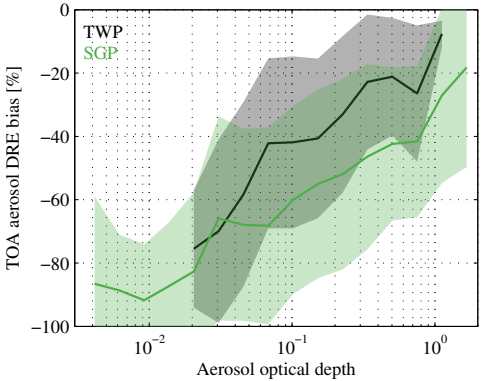
Global implications

- Aerosol that goes undetected is consistent with random noise considerations
  - CALIPSO's SNR is too low to detect all aerosol during both day and night.

- Even for large aerosol optical depths, the bias remains significant
- The global mean ocean AOD as measured by CALIPSO is 0.09

  (Winker et al., 2013)
- AOD=0.09 → -35% to -50% aerosol DRE bias at the two ARM sites

	Clear-sky ocean
Passive sensor-based	$-5.0\ Wm^{-2}$
(Yu et al. *ACP* 2006)	
CALIPSO-based	$-3.21\ Wm^{-2}$ (-36%)
(Oikawa et al. *JGR* 2013)	
CALIPSO-based	$-2.6\ Wm^{-2}$ (-48%)
(Matus et al. *JCLIM* 2015)	



Conclusions

- The results presented here strongly suggest that newer estimates of the global aerosol DRE that rely solely on CALIPSO aerosol observations (Oikawa et al. *JGR* 2013); Matus et al. *JCLIM* 2015) are biased weak (i.e. too small in magnitude).
- This study demonstrates that our knowledge of the global aerosol DRE remains incomplete.
- While CALIPSO allows for more consistent global estimates of the aerosol DRE in all scene types, its detection sensitivity is likely not sufficient for detecting all radiatively-significant aerosol.
- Passive sensors outperform CALIPSO in observing thin AOD since CALIPSO is sensitive to the backscatter in a relatively small volume while passive sensors measure the vertically-integrated scattering.
- However, the limitation of accurate passive retrievals to cloud-free ocean as well as potential biases from cloud contamination makes fully and accurately assessing global aerosol DRE difficult.

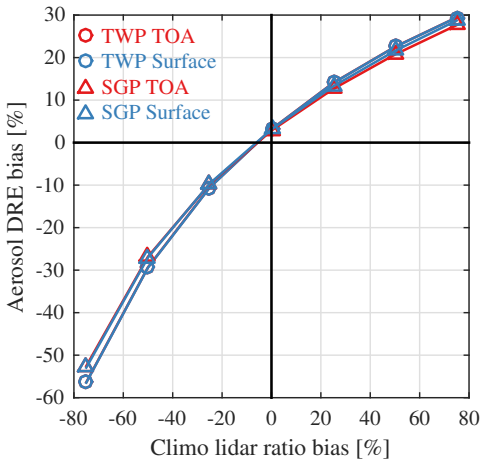
We don't know the global aerosol DRE

CALIPSO-inferred aerosol direct radiative effects: Bias estimates using ground-based Raman lidars; TJ Thorsen, Q Fu; Journal of Geophysical Research, 2015.

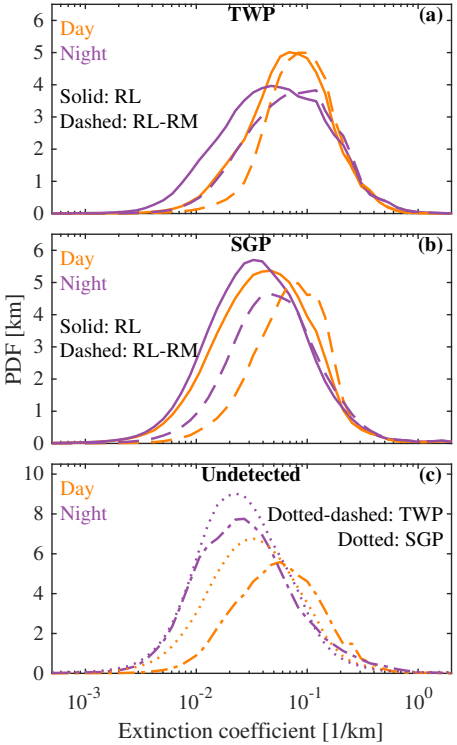
Effect of assumed lidar ratios

- CALIPSO's processing:
  Detect → cloud/aerosol → 6 aerosol subtypes → lidar ratio → extinction → flux

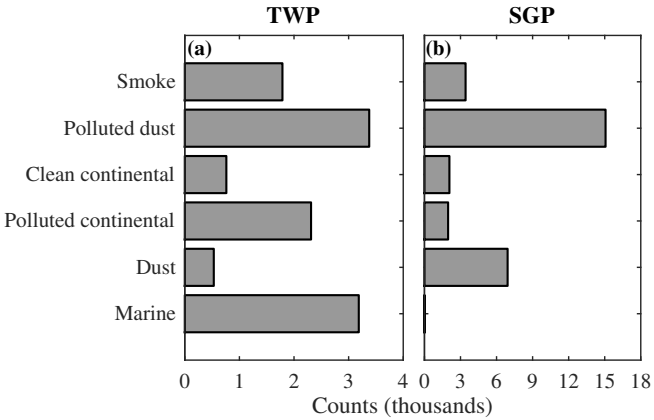
- The wavelength difference between CALIPSO (532 nm) and RL (355 nm) precludes a direct assessment of CALIPSO's lidar ratios. Instead the aerosol DRE is computed with
  1. Directly retrieved RL extinction
  2. Lidar ratio fixed (climatology±bias)
- If the selection of lidar ratio by CALIPSO can reproduce the climatological value at a particular location, then the aerosol DRE can be accurately calculated.

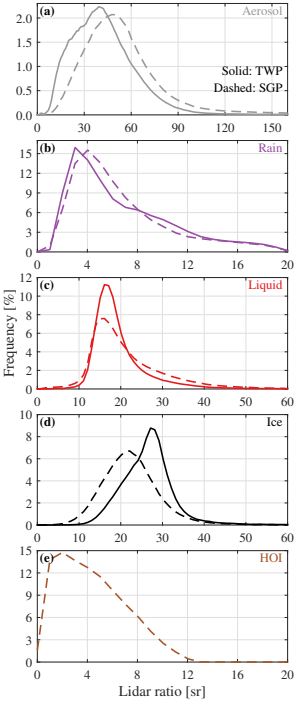


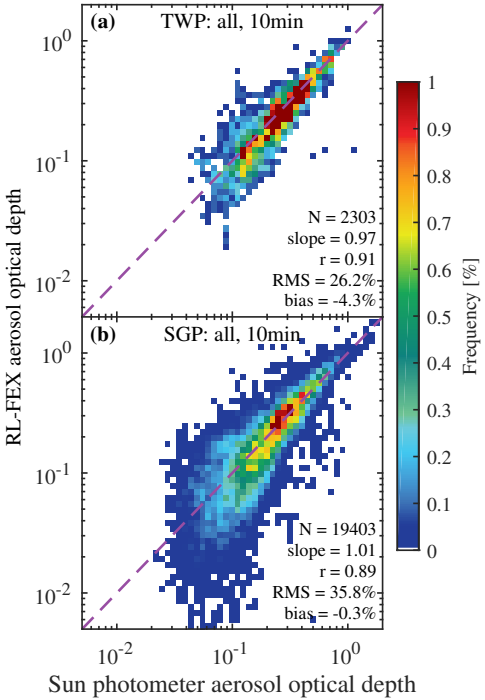
- Rogers et al. *AMT* (2014) found approximately a +20% bias in CALIPSO's lidar ratio which would correspond to about +10% bias in the aerosol DRE.


TWP
(a)
Day
Night
Solid: RL
Dashed: RL-RM
SGP
(b)
Day
Night
Solid: RL
Dashed: RL-RM
PDF [km]
Undetected
(c)
Day
Night
Dotted-dashed: TWP
Dotted: SGP
Extinction coefficient [1/km]

CALIPSO aerosol layer classifications




(a)
Aerosol
Solid: TWP
Dashed: SGP
(b)
Rain
(c)
Liquid
(d)
Ice
(e)
HOI
Frequency [%]
Lidar ratio [sr]


(a) TWP: all, 10min
N = 2303
slope = 0.97
r = 0.91
RMS = 26.2%
bias = -4.3%
(b) SGP: all, 10min
N = 19403
slope = 1.01
r = 0.89
RMS = 35.8%
bias = -0.3%
RL-FEX aerosol optical depth
Sun photometer aerosol optical depth
Frequency [%]
10^0
10^-1
10^-2
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0